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Advances of the FRIB project

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The Facility for Rare Isotope Beams (FRIB) Project has entered the phase of beam commissioning starting from the room-temperature front end and the superconducting linac segment of first 15 cryomodules. With the newly commissioned helium refrigeration system supplying 4.5 K liquid helium to the quarter-wave resonators and solenoids, the FRIB accelerator team achieved the sectional key performance parameters as designed ahead of schedule accelerating heavy ion beams above 20 MeV/u energy. Thus, FRIB accelerator becomes world's highest-energy heavy ion linear accelerator. We also validated machine protection and personnel protection systems that will be crucial to the next phase of commissioning. FRIB is on track towards a national user facility at the power frontier with a beam power two orders of magnitude higher than operating heavy-ion facilities. This paper summarizes the status of accelerator design, technology development, construction, commissioning as well as path to operations and upgrades.

Keywords: Accelerator; rare isotope; heavy ion; FRIB; linac.

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1. Introduction

During the past decades, accelerator-based facilities, such as Spallation Neutron Source (SNS), Japan Particle Accelerator Research Complex (J-PARC), the Swiss SNS at Paul Scherrer Institute (PSI) and Los Alamos Neutron Science Center (LANSCE), advanced the frontier of proton beam power to the 1 MW level.[1] The Facility for Rare Isotope Beams (FRIB) is designed to advance the frontier of heavy-ion beam power by more than two orders of magnitude, i.e., to 400 kW.[2]

In August 2014, the US Department of Energy's Office of Science (DOE-SC) approved Critical Decision-3b (Approve Start of Technical Construction) for the FRIB project. The total project cost for FRIB is $730 M, of which $635.5 M is provided by DOE and $94.5 M is provided by Michigan State University (MSU). The project will be completed by 2022. When completed, FRIB will provide access to completely uncharted territory at the limits of nuclear stability, revolutionizing our understanding of the structure of nuclei as well as the origin of the elements and related astrophysical processes.

Three years after the start of technical construction, the FRIB project entered the stage of phased commissioning with the heavy-ion beams (Ne, Ar, Kr and Xe) following the completion of the room-temperature part of the front end, as shown in Fig. 1 and Table 1. In this paper, we present the main results of the first three stages of beam commissioning that have been completed covering nearly all major accelerator systems including the electron cyclotron resonance (ECR) ion source, the radio-frequency quadrupole (RFQ), the cryomodules of $\beta = 0.041$ and 0.085

Fig. 1. FRIB driver linac viewed from the lower low-energy-beam-transport (LEBT) towards the superconducting linac in the accelerator tunnel at the beginning of beam commissioning in 2017.

Table 1. Stages of accelerator readiness (ARR) for the phased beam commissioning of the FRIB accelerator.

Phase	Area with beam	Beam energy [MeV/u]	Date
ARR1	Front end	0.5	2017-7
ARR2	Plus $\beta = 0.041$ cryomodules	~ 2	2018-5
ARR3	Plus $\beta = 0.085$ cryomodules	~ 20	2019-2
ARR4	Plus LS2 $\beta = 0.29$ and 0.53 cryomodules	~ 200	2020-3
	Plus lithium charge stripper	—	2020-10
ARR5	Plus LS3 $\beta = 0.53$ cryomodules	> 200	2020-12
ARR6	Plus target and beam dump	> 200	2021-9
Final ARR	Integration with pre-existing facility	—	2022-6

quarter-wave resonators (QWRs), the liquid helium refrigeration plant operating at 4 K temperature and supporting systems including RF, power supply, diagnostics, vacuum, hardware and high level controls, machine protection, personnel protection, physics applications and integration.

Subsequently, we discuss resolutions to some leading technical issues including low-sensitivity loss detection and machine protection, charge stripping with liquid metal and microphonics suppression. We continue with status reports on infrastructure build-up of the MSU cryogenics initiative and the superconducting RF (SRF) Highbay. We conclude with challenges in the beam power ramp-up and the path forward of beam energy upgrade.

2. Phased Commissioning

The commissioning of the FRIB complex is divided into seven phases spanning over six years, as shown in Table 1.

2.1. *Front-end beam commissioning*

The main purpose of front-end (ARR1) commissioning was to integrate room-temperature accelerator systems together with the newly built civil infrastructure including electricity and water. For simplicity, we avoided cryogenics and focused on establishing needed processes for a newly constructed accelerator facility. Emphases were on hazard mitigation for personnel safety (electrical hazard from the high voltage platform and radiation hazard from the source plasma) and conduct of operations.

The ARR1 commissioning goals were promptly achieved with both Ar and Kr beams produced from the ion source, transported through the LEBT with pre-bunching, and accelerated by the RFQ to beam energy of 0.5 MeV/u with full design transmission efficiency of about 85% (Fig. 2).[3]

2.2. *First three Cryomodules' beam commissioning*

The main purpose of ARR2 commissioning was to perform integrated tests of nearly all accelerator systems with emphasis on cryogenics and cryomodules. Figure 3

Fig. 2. Front-end (ARR1) beam commissioning in 2017. (Top) Aerial view of the room-temperature lower LEBT including the 80.5 MHz RFQ. (Bottom) Accelerator physicists and operators working at the front-end control room during the ARR1 beam commissioning.

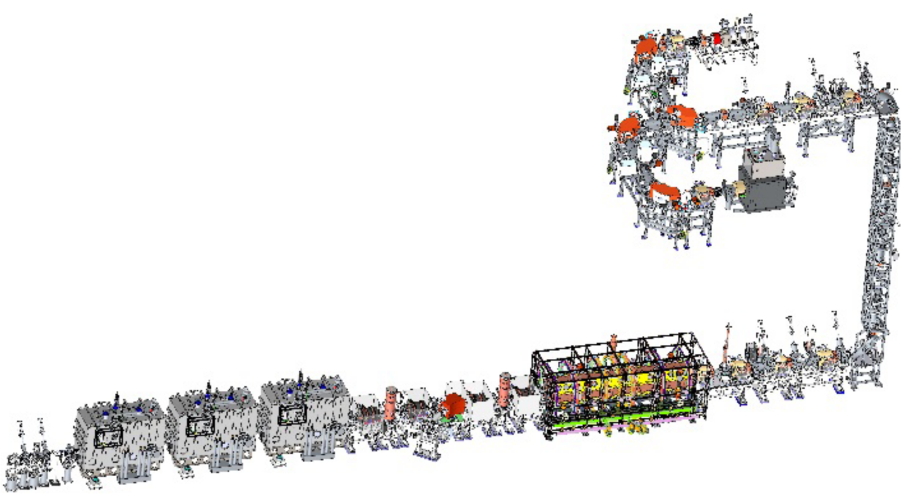

Fig. 3. Scope of ARR2 beam commissioning in 2018 including the front end, the first three cryomodules of $\beta = 0.041$ QWR of FRIB linac segment 1 (LS1) and a temporary diagnostics station.

shows the beamline layout extending from the ion source at the surface to the linac tunnel underground including three $\beta = 0.041$ cryomodules and a temporary diagnostics station. After establishing the oxygen deficiency hazard control system,[4] we first started the commissioning of the FRIB cryoplant at 4 K temperature (Fig. 4), followed by the commissioning of the cryo-distribution and the cool down of the cryomodules.[5] The tunnel access control system is activated for radiation hazard mitigation before we proceed with RF conditioning of the SRF resonators. As cryomodules have been 100% tested at multiple stages (cavity/couple/solenoid individual tests and cryomodule bunker tests), the conditioning in tunnel proceeded rapidly.

The ARR2 commissioning goals were again promptly achieved with both Ar and Kr beams from the front end accelerated by the three cryomodules to beam energies above 2 MeV/u with 100% transmission efficiency (Fig. 5). The beam duty factor was gradually increased to 30% limited by the temporary beam dumping Faraday cup. The Ar^{9+} beam power of 66 W at 1.5 MeV/u would correspond to about 38 kW of power on the target had the beam been accelerated to the full energy of 285 MeV/u at 100% duty cycle. An unexplained observation was the neutron signal detected at unexpected low energy of 1.8 MeV/u,[6] possible due to light-element contaminants in the beam striking the unbaked Faraday Cup at the diagnostics station.

2.3. *Linac segment* 1 *with QWR Cryomodule beam commissioning*

ARR3 aims at accelerating the beams of various ion species (Ne, Ar, Kr and Xe) above 20 MeV/u energy passing the charge stripper. 3 $\beta = 0.041$ accelerating cryomodules, 11 $\beta = 0.085$ accelerating cryomodules and 1 $\beta = 0.085$ buncher cryomodule were installed in the FRIB tunnel and cooled down to 4 K temperature by liquid helium (Fig. 6). Again, the tunnel access control system is activated for radiation hazard mitigation before we proceed with RF conditioning of the 104 SRF resonators contained in 15 cryomodules. As cryomodules have been 100% tested at multiple stages (resonator/coupler/solenoid individual tests and cryomodule bunker tests), the conditioning in tunnel proceeded rapidly. Both resonators and solenoids in the cryomodules were energized to the full accelerating fields ready for beam in a few days.

To allow beam acceleration to energies well above the Coulomb barrier, the FRIB tunnel was designated as radiation restricted area with strict personnel access control. Shielding is the primary line of defense. Since beam commissioning is progressing in parallel to equipment installation, there exists temporary penetrations to the FRIB tunnel including loading shafts, unsealed cable conduits, and beam line opening to the target hall. Radiation monitors are mounted at these temporary penetrations to monitor and safety interlock possible prompt radiation. Radiation survey is mandated to monitor induced radiation before planned access.

The ARR3 commissioning goals were again promptly achieved with Ne, Ar, Kr and Xe beams accelerated to beam energies all above 20 MeV/u with 100%

Fig. 4. Commissioning of the FRIB helium refrigeration system (cryoplant) at 4 K in 2017. (Top) The FRIB cryoplant established to supply liquid helium to the entire FRIB accelerator facility. (Bottom) The FRIB cryogenics team during the cryoplant 4 K commissioning in the FRIB cryogenic control room.

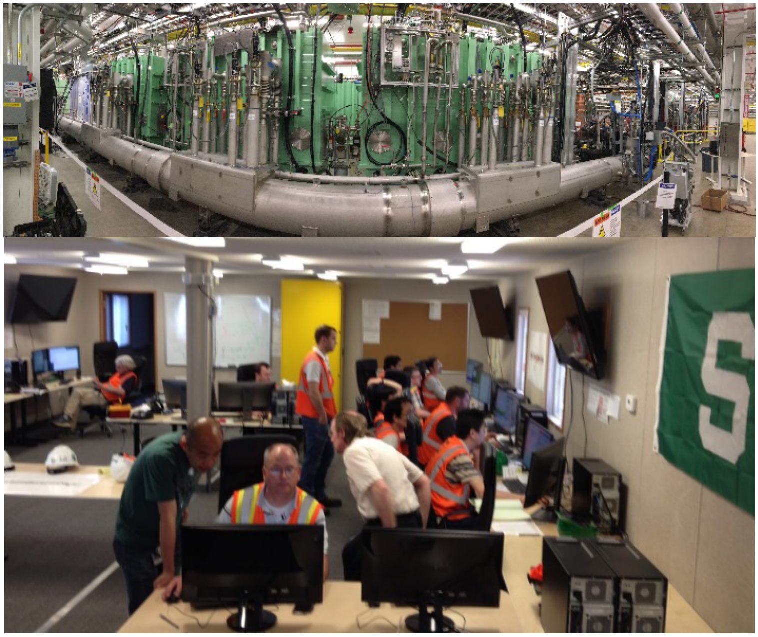

Fig. 5. ARR2 beam commissioning in 2018 including the front end, the first three cryomodules of $\beta = 0.041$ QWR of FRIB linac segment 1 (LS1) and a temporary diagnostics station. (Top) Aerial view of the first three QWR cryomodules. (Bottom) The ARR2 commissioning team at the FRIB main control room.

transmission efficiency through cryomodules (Fig. 6). The beam duty factor varied from 0.01% to continuous wave with total beam power limited by the temporary beam dump of 500 W. The carbon charge stripper was used to strip the beam to a higher charge state at the end of acceleration (Fig. 7). A charge selector was used downstream of the first 45° dipole magnet in the folding segment 1.

2.4. *Forthcoming beam commissioning*

Future ARR4 aims at acceleration of heavy-ion beams like Ar to about 200 MeV/u using the 15 QWR cryomodules in linac segment 1 as well as the 12 $\beta = 0.29$ and 12 $\beta = 0.53$ HWR cryomodules in linac segment 2 meeting the so-called key performance parameters of the FRIB driver linac, as shown in Fig. 8. In preparation for the ARR4, the FRIB helium refrigeration system has been commissioned to produce liquid helium at 2 K temperature in the QWR of the linac segment 1 cryomodules.

ARR5 aims at steering the beam through the superconducting dipole magnets in folding segment 2 for further acceleration with the remaining 6 $\beta = 0.53$ HWR cryomodules in linac segment 3 and transporting to the end of linac segment 3 beam dump. ARR5 marks the completion of beam commissioning in the FRIB driver linac.

Fig. 6. ARR3 beam commissioning in 2019 including the front end, 15 cryomodules of both $\beta = 0.041$ and 0.085 QWR of FRIB linac segment 1 (LS1) and part of the FRIB folding segment 1. (Top) View inside the FRIB accelerator tunnel with 15 commissioned QWR cryomodules of linac segment 1 to the left and $\beta = 0.53$ half-wave resonator (HWR) cryomodule of linac segment 3 to the right. (Bottom) The ARR3 commissioning team at the FRIB main control room.

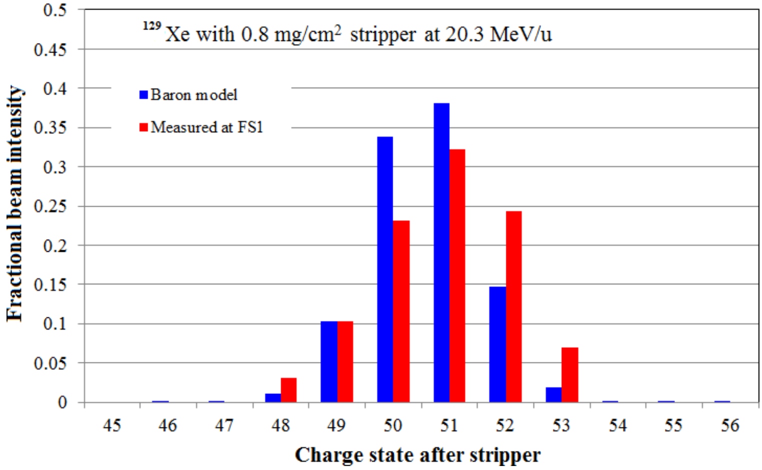

Fig. 7. Comparison of measured and calculated 129Xe beam charge-state distribution after passing the carbon charger stripper at the energy of 20 MeV/u.

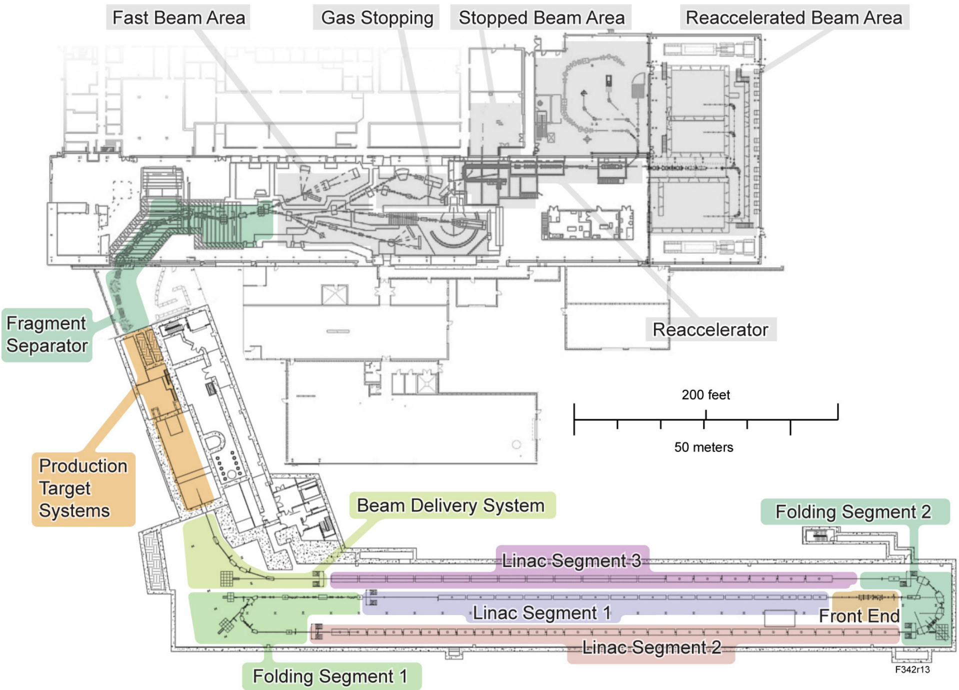

Fig. 8. (Color online) Schematic layout of the FRIB accelerator complex. The primary beam is generated from the front end and accelerated through linac segment 1, folding segment 1, linac segment 2, folding segment 2, linac segment 3 and beam delivery system striking the production target. The secondary rare isotopes produced from the target are transported through the fragment separator to the areas of fast beam, stopped beam and reaccelerated beam for user experiments. The colored areas indicate FRIB new construction.

ARR6 integrates the driver linac accelerator with the production target for the rare isotope and beam dump for the primary beams. This step involves integration of FRIB accelerator systems to the experimental systems

The final ARR integrates the new-construction driver linac, production target and fragmental separator with the existing experimental facilities of the FRIB laboratory. Upon completion, the facility is ready for scientific users. Upon the start of user operations, it is expected to take up to five years before the facility reaches the full design specification of 400 kW beam-on-target power.

3. Technical Issue Resolution

Major technical issues have been the focus of R&D since project start. These issues are being resolved and demonstrated during the staged beam commissioning.

3.1. *Machine protection and Low-sensitivity beam loss detection*

The issue of poor detection sensitivity of low-energy heavy ions and the consequent challenges in machine protection is addressed by multi-layer, multi-time scale machine protection system designs.[7] The initially installed beam attenuator for machine protection was removed after the beam chopper was validated and monitored limiting the beam duty cycle before the interim beam dump. The fast machine protection based on the differential beam current signal was demonstrated mitigating the stray beam within the required 35 μs time duration (Fig. 9). In addition,

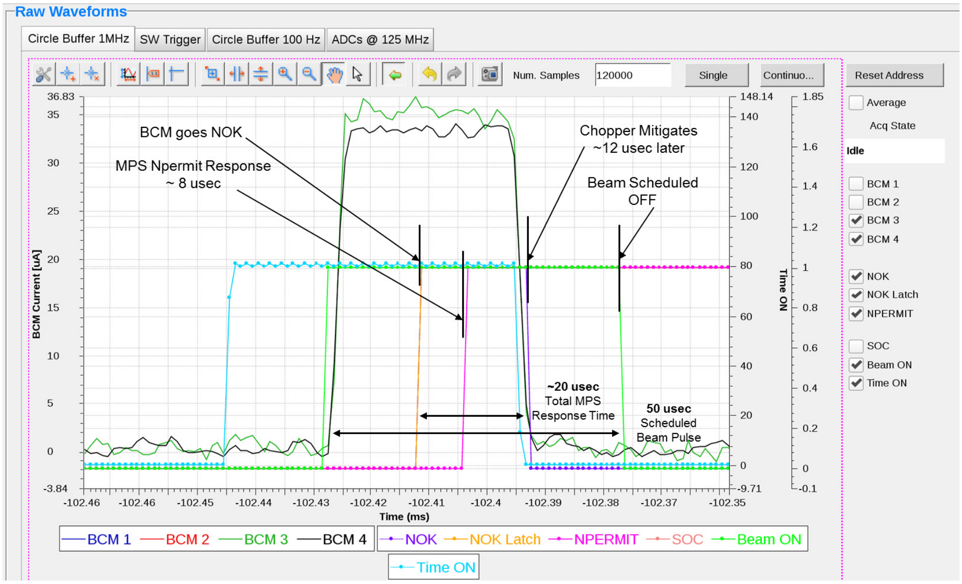

Fig. 9. Demonstration of fast machine protection with the differential current monitor signal.

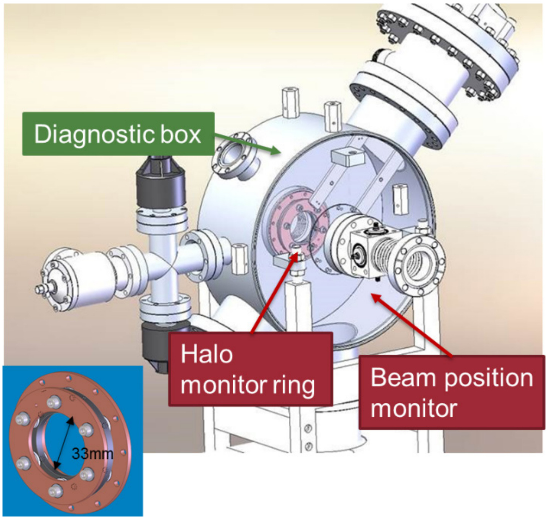

Fig. 10. Halo monitor rings installed in the warm section between the cryomodules.

the halo monitor rings installed between the cryomodules were highly sensitive to both ion and electron signals at nA level (Fig. 10). The fast thermometry sensors installed inside the cryomodule detected beam loss induced heating at 0.1 K level.

3.2. *High-power charge stripping*

Development of liquid lithium charge stripper capable of withstanding high beam power of heavy ions proceeded with the demonstration of continuous lithium circulation with the electromagnetic pump. Lithium film was established inside the primary chamber housed inside the secondary vessel[8] (Fig. 11). Credited controls are implemented to ensure configuration management and conduct of operations.

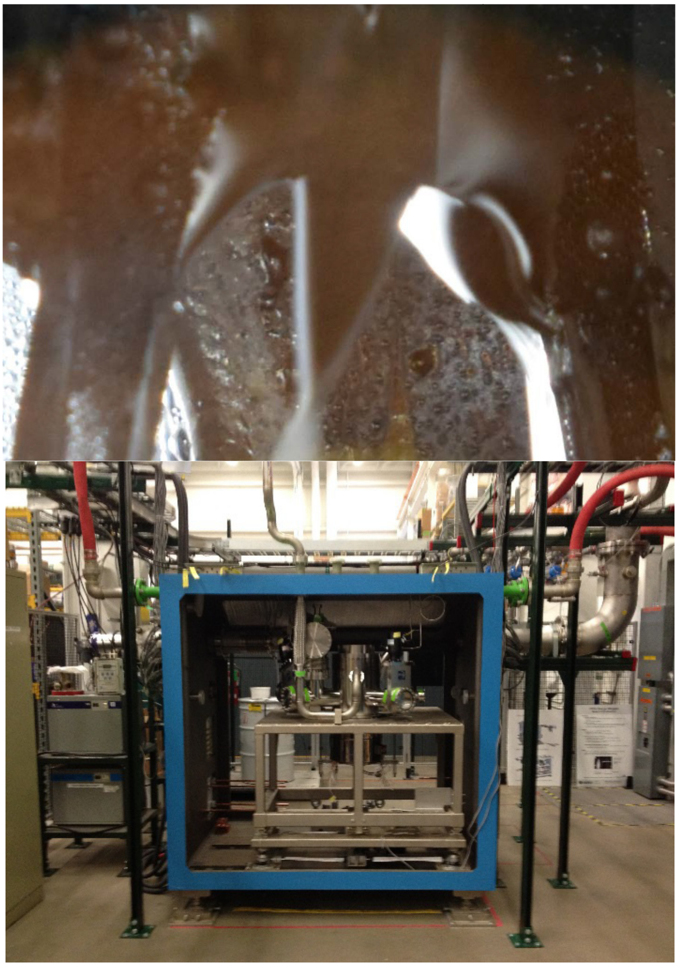

Fig. 11. Liquid lithium charge stripper module (bottom) and the established lithium film (top).

3.3. *Microphonics suppression*

Microphonics is known to compromise the performance of SRF resonators. The situation is more challenging for FRIB as the cryoplant containing noisy compressors is located in the same building of the FRIB accelerator (Fig. 10). Precaution in compressor design & installation is key to microphonics mitigation. Design of the innovative "bottom-up" cryomodule carefully incorporated microphonics suppressing considerations including top suspended cryogenic headers for vibration isolation.[9–11] Effectiveness of microphonics mitigation is monitored by tunnel

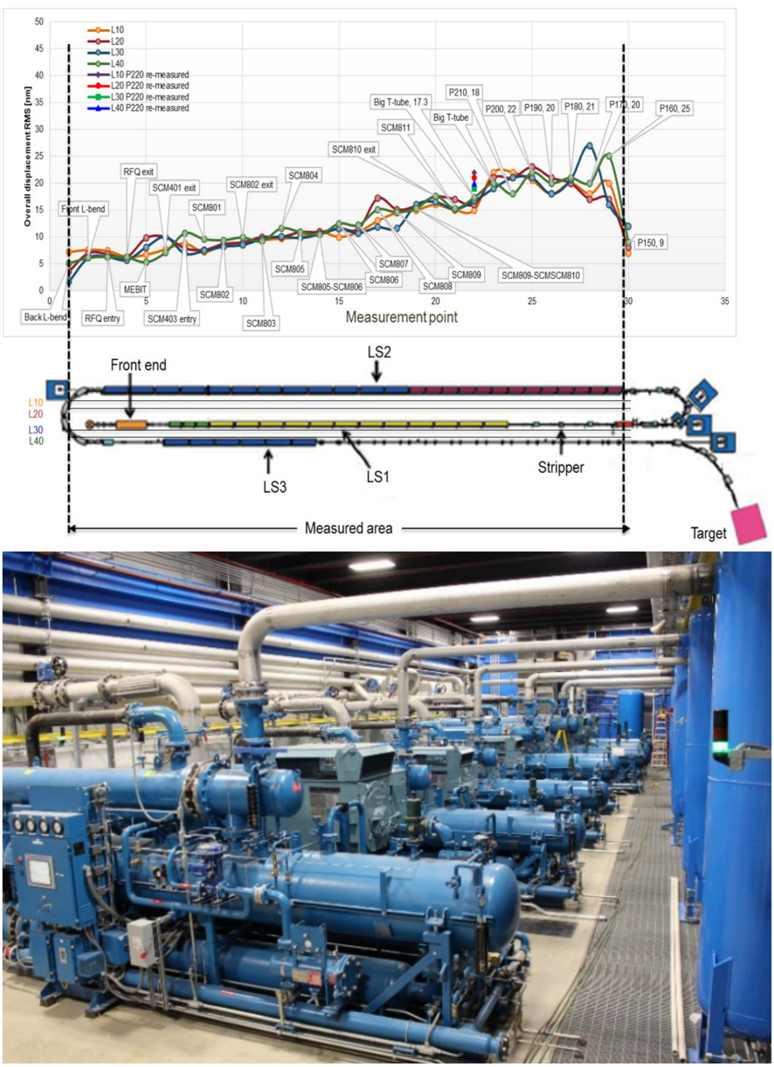

Fig. 12. Cryoplant compressors located in the FRIB building (bottom) and the measured tunnel vibration (top).

measurement of vibrational spectrum (Fig. 12). SRF cavity locking issues that occurred at initial cool down were promptly resolved by iteration on valve controls logic and by provisions for liquid helium supply from a 10,000 L Dewar.

4. Infrastructure Growth

Michigan State University has heavily invested in the infrastructure necessary for FRIB development and for future research including funding of the cryogenics initiative, establishing the SRF Highbay for SRF resonator processing and certification at mass production capacity, and recruitment of subject matter experts from over the world covering all disciplines of accelerator physics and engineering needed for the development of high-power hadron accelerators.

Fig. 13. The SRF highbay (top) and the cryomodule assembly area (bottom) housing six parallel assembly lines delivering more than one cryomodule per month.

4.1. *SRF Highbay and Cryogenics assembly building*

To meet the FRIB project schedule, MSU has built up the capacity of mass production and certification of more than one cryomodule per month. The 2500 m^2 "SRF Highbay" houses areas for material inspection, cavity mechanical coordinate measurements, vacuum furnace degassing, chemical etching, high-pressure water rinsing, SRF coupler conditioning, cold mass assembly and cryomodule testing (Fig. 13). This facility, together with the cryomodule assembly area and the machine shop, supports the production throughput of testing five resonators per week and one cryomodule per month.[12] In addition to the buffered chemical polishing (BCP) used for FRIB resonators, the electro-polishing (EP) facility is being established to support FRIB upgrade. Furthermore, a new 1440 m^2 cryogenic assembly building is under constructed to house future cryomodule and superconducting magnet developments and production.

Fig. 14. The MSU cryogenics initiative programs. (Top) Professor Ganni lecturing at the cryogenic class at the MSU. (Bottom) Students visiting the FRIB helium refrigeration system.

4.2. *The MSU cryogenics initiative*

The MSU cryogenics initiative directed by Ganni aims at building up the national cryogenic knowledge base through education and training of cryogenic physicists and engineers, pursuing advanced cryogenic process design and state-of-the-art technology development and supporting large-scale cryogenic systems associated with major accelerator facilities. Both regular university courses and condensed US Particle Accelerator School courses are offered along with traineeship programs. The initiative's primary R&D areas are main compressor efficiency improvements, low-level impurity removal and small 2 K system for laboratory use (Fig. 14).[13]

5. Power Ramp-Up and Upgrade

FRIB expects to ramp-up beam power to 400 kW in about four years after the completion of the construction project (Fig. 15), which is about two order-of-magnitudes higher than any existing heavy-ion accelerator in the power frontier.[1,14] Challenges include establishing the 28-GHz superconducting ECR ion source, the liquid lithium charge stripper and the high-power charge selector, facilitating beam halo cleaning and collimation and improving the reliability and availability of the facility.

The first step of FRIB upgrade is to double the driver linac output energy from the baseline to above 400 MeV/u. Space reserved in the FRIB tunnel will be filled with additional 11 cryomodules of $\beta = 0.65$ elliptical resonators. Prototype resonators are being fabricated by the industrial vendors. In house, BCP processing

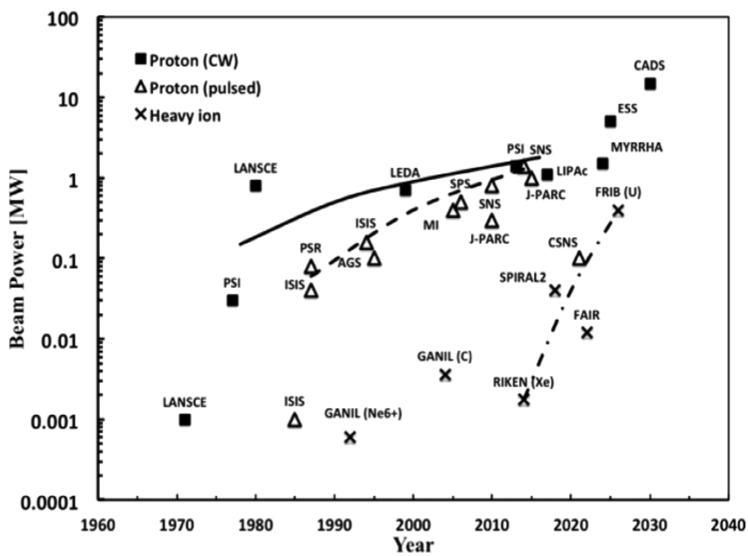

Fig. 15. Evolution of hadron accelerator beam power. The three curves indicate the growth of power of continuous-wave (CW) proton beams, pulsed proton beams and heavy-ion beams, respectively.

Fig. 16. SRF cavity for FRIB upgrade being processed at the MSU and Argonne National Laboratory.

and certification results (Fig. 16) are to be benchmarked with those from Argonne using EP processing. The cryogenic distribution is configured so that the prototype cryomodule for FRIB upgrade can be readily connected after it is built. The raised energy is expected to significantly enhance the rare isotopes yield. It will also reduce the stress on the production target and the beam dump.

6. Conclusion

At a time when accelerator projects at the high-energy frontier are experiencing difficulties in gaining financial support, projects at the high-intensity and high-power frontier are flourishing worldwide. Demands for such accelerators extend from science to applications, and for primary beams from proton to heavy ions. Efforts worldwide are preparing the technologies and designs meeting the requirements of user facilities with high reliability, availability, maintainability, tunability and upgradability.

The FRIB project is designed to advance the frontier of heavy-ion beam power by more than two orders of magnitude. Nearly five years after the start of technical construction of the project, FRIB is progressing on schedule and on cost with beam commissioning proceeded through the first 15 of the total 46 superconducting cryomodules and heavy ions accelerated above 20 MeV/u. At such energy, FRIB has already become world's highest-energy heavy ion linear accelerator, as well as world's largest heavy ion linear accelerator using super-conducting RF technology. Operations for scientific users are expected to start as planned in 2022.

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